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RADIUM
for
Therapeutic Purposes

BY

CHARLES F. WHITTEMORE, M.Sc.

Chief Physicist, Research Laboratories,
The Radium Company of Colorado, Inc.

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THE RADIUM COMPANY OF COLORADO, INC.
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INTRODUCTION

This publication has been prepared in response to many requests from members of the medical profession for information on the subject of radium. The author has undertaken to present a concise review of the chief physical and chemical properties of radium and a summary of authoritative information in regard to its therapeutic application. It is also the purpose of this booklet to introduce equipment designed for use in radium therapy with special reference to the installation of radium emanation stations. Owing to the highly specialized character of this branch of science, a brief summary of the fundamental principles of radioactivity is indispensable for a thorough understanding of the therapeutic application of radium and its products. It will not be out of place therefore to state, at the beginning, some of the laws of radioactivity.

THEORY OF RADIOACTIVITY

The fundamental principle underlying the peculiar properties of radioactive elements is the spontaneous disintegration of their atoms into atoms of physically and chemically different substances. According to the theory of Rutherford[1] and Bohr,[2] an atom of any element is composed of an extremely minute nucleus of positive electricity surrounded by an outer system of negative electrons rotating around the center. The total electric charge of the rotating electrons is just enough to balance the positive electricity of the nucleus. The arrangement and number of electrons and the nuclear charge determine the characteristics of the atom. The forces tending to hold the nucleus intact are very powerful and no chemical or physical means have ever been devised whereby such a center can be modified in any way. However, the atoms of some elements are less stable than others and a disruption of the nucleus occurs spontaneously. The result is practically a violent explosion of the atom and complete rearrangement of the constituents of both inner and outer systems to form an atom of an entirely different element. Usually this phenomenon is accompanied by the expulsion of electrically charged particles traveling at very high velocities and sometimes by a type of x-radiation also. Such substances, which are continuously undergoing spontaneous disintegration, are called radioactive.

For example, consider the case of radium. The disintegration of any given amount of radium takes place very gradually, although the disruption of an individual atom is a sudden change of explosive nature. However, the atoms of radium are not all exploding at once but in a more random way—now one, then another—and always at such a rate that, during equal periods of time, the number of atoms which disintegrate, is always the same fraction of the total number present. In any mass of radium some of the atoms are ex-

[1]Rutherford, Phil. Mag. 21, p. 669, 1911.
[2]Bohr, Phil. Mag. 26, p. 1-25, 476-502.

tremely stable, while others possess various degrees of stability approaching that ultimate condition which ends in their disruption and rearrangement of their constituent parts. When the disruption of the radium atom occurs, a positively charged particle of relatively small mass, now known to be helium, is suddenly expelled at a high velocity, while the residual atom by a rearrangement of the electrons becomes an atom of a new substance. The particle expelled is called the alpha ray while the other product of the radioactive change is called radium emanation.

The new product, radium emanation, is a gas which is even less stable than the radium, consequently it disintegrates in a similar manner but at a much more rapid rate. The unfortunate selection of the name "emanation" for this substance has led to some confusion because it gives the impression of something imponderable, whereas radium emanation is just as real as any other gas. To avoid any such misunderstanding, Sir William Ramsey has proposed the name "Niton." There are some advantages, however, in the name radium emanation, since it implies at once the close relationship of the emanation to the parent substance radium. As in the case of radium itself, the expulsion of an alpha particle from the atom of emanation causes the residue to coalesce into another new body called RaA which, by further consecutive changes gives rise to the series RaB and RaC, and so on until stable elements are reached.

RaA, B and C are found on any surface which may remain in contact with the radium emanation and consequently are often referred to collectively as the "active deposit." The manner in which these radioactive changes occur and the types of radiation accompanying them are indicated in the following table:

TABLE I.

THE URANIUM RADIUM SERIES

ELEMENT	RADIATION	HALF VALUE PERIOD		ATOMIC WEIGHT
Uranium 1	Alpha	5.5×10^9	years	238
Uranium X_1	Beta and Gamma	24.6	days	234
Uranium X_2	Beta	1.15	mins.	234
Uranium 2	Alpha	2.1×10^6	years	234
Ionium	Alpha	1.4×10^5	years	230
Radium	Alpha	1730	years	226
Radium Emanation	Alpha	3.85	days	222
Radium A	Alpha	3	mins.	218
Radium B	Beta and Gamma	26.7	mins.	214
Radium C	Beta and Gamma	19.5	mins.	214
Radium C^1	Alpha	10^{-6}	sec.	214
Radium C_2 (Branch Prod)	Beta and Gamma	1.3	mins.	210
Radium D (Radio Lead)	Slow Beta	15.83	years	210
Radium E	Beta and Gamma	4.8	days	210
Radium F (Polonium)	Alpha	136	days	210
End				206

It will be observed that the penetrating gamma radiation is not directly emitted by either radium or radium emanation but instead it comes from a disintegration product RaC (i. e. RaC and RaC_2 taken together). Therefore it is radium C which ordinarily most concerns the radium therapist and if a supply of RaC is available he possesses a source of the highly penetrative radiation. The extremely short period of RaC, however, precludes the possibility of isolating and using it by itself for general therapeutic purposes, although the active deposit, RaABC may be so used. Going further back in the series, however, we come to radium emanation which has a half-value period of 3.85 days and being the only gaseous member of the entire radium disintegration series, is readily separable. It possesses all of the characteristics of a gas and can be manipulated and purified as such.

Yet radium emanation alone emits only the alpha type of radiation and would, therefore, be worthless by itself. The fact that it forms RaA so rapidly and in a few hours

has produced the full equilibrium amount of RaB and C, determines its importance therapeutically.

In other words, radium alone is only a feebly radioactive element and the powerful, penetrative radiation obtained from a tube of radium is due to the growth of radium emanation and RaA, B, and C from the parent substance, radium. In thirty days a newly sealed tube of radium salt, attains a point of equilibrium when the emanation and the active deposit have reached a maximum and their growth just balances their decay. Thirty days after preparation, therefore, a radium salt, if sealed in a gas tight tube, will emit its maximum penetrating gamma radiation. Moreover, the radium emanation may be separated from radium and enclosed in a gas tight tube which may be used exactly like a tube of radium with allowance of course for the more rapid rate of decay. And finally the "active deposit" may be collected and used, although its extremely short life permits only a limited application.

TYPES OF RADIATION

There are three distinct types of radiation emitted from radioactive bodies which have been called the alpha, beta and gamma rays. A very close analogy exists between these rays and the rays produced in an ordinary X-ray tube. The alpha rays are analogous to the canal rays, beta rays are practically the same as the cathode rays, while gamma rays are very similar to the Roentgen rays. The principal differences are accounted for by the fact that the alpha and beta particles are expelled at higher velocities than the canal and cathode rays respectively; and gamma rays are more penetrating than X-rays.

Another very practical difference lies in the manner in which these rays are produced. In the case of Roentgen rays, large quantities of electrical energy are expended, while rays from radioactive substances like radium are produced spontaneously.

ALPHA RAYS

Alpha rays are positively charged particles projected at enormous velocities which range from 1.4 to 2.2×10^9 centime-

ters per second, or in other words, approximately one-tenth the velocity of light. Rutherford and Royds[1] have shown that the alpha particle is identical with an atom of helium, carrying two unit positive charges. Naturally such particles of appreciable mass traveling at such high velocity possess extraordinary kinetic energy. Therefore, of the three types of radiation, the alpha ray is by far the most powerful agent in ionizing gases. On the other hand, the penetrating power of the alpha rays is exceedingly small, a sheet of ordinary writing paper being sufficient to absorb them completely. In any tube of radium or radium emanation, all the alpha rays are absorbed by the glass, and in flat applicators, the alpha particles are absorbed by the varnish or enamel. Owing to the charge carried by alpha rays, they are deflected in a magnetic or electric field, but the deviation is small unless very powerful fields are employed. The range of the alpha rays in air is only a few centimeters; for example, the high velocity alpha particles from radium C have a range of only seven centimeters in air at standard pressure and laboratory temperature of about 15° C. These considerations of short range and extremely low penetrating power show why the alpha rays are of little practical value in radium therapy according to present knowledge. If the active deposit is injected, the alpha rays are used to their full extent, but such practice is rather limited at present. It is not unlikely, however, that the enormous kinetic energy of the alpha particles will sometime be fully utilized.

BETA RAYS

The beta radiation is also corpuscular in nature, that is, it consists of negatively charged corpuscles or electrons expelled at a velocity in some cases nearly equal to the velocity of light. The ionizing power of the beta ray is only one hundredth part as great as that of the alpha radiation, but the penetrating power is approximately one hundred times greater. For example, the beta rays from radium salts sealed in a glass tube are only slightly absorbed by the thin glass walls and are not completely absorbed unless the con-

[1]Rutherford and Royds, Phil. Mag. 17, p. 281, 1909.

tainer is surrounded by a 2-millimeter layer of lead. Since the beta rays carry a negative charge and are of relatively small mass, they are very readily deflected in a magnetic or electric field and in a direction opposite from the alpha particles which carry positive charges. The average range of the beta ray in air is about 250 cms. From the therapeutic standpoint beta rays possess considerable importance, and allowance must always be made for their effect when using radium preparations. If the beta radiation is not desired, two or three millimeters of lead will effectively absorb it, and other filters such as brass, silver or platinum may be used for the same purpose. In regulating the effect on tissues it must be remembered that unless the beta radiation is cut off by a suitable thickness of metal, the superficial tissues will be subjected to a much greater action than the underlying layers, which may result in surface injury, or beta-ray burns. The beta rays are very useful, however, where only superficial effects are required or where the radium is in direct contact with the malignant cells.

GAMMA RAYS

The most penetrating radiation consists of the so-called gamma rays which, unlike the alpha and beta rays, are not corpuscular in nature, but consist of electromagnetic disturbances similar to ordinary light waves. There is no essential difference between gamma rays and X-rays and ordinary light. They all belong to a class of electromagnetic waves. The wave length of the gamma ray is by far the shortest, being of the order of 10^{-9} cm., while that of the X-ray is about 10^{-8} and that of light is of the order of 10^{-5}. By virtue of the short wave length, the gamma rays possess greater penetrating power than X-rays, hence the superiority of radium rays over X-rays in therapeutics. To use the terminology of the X-ray therapist, the gamma rays of radium are "harder" than even the hardest X-rays ever produced. With respect to beta rays, the gamma rays possess only about one one-hundredth part of the ionizing power but are from ten to one hundred times more penetrating. Several centimeters of lead will not completely stop this type of radiation, and

correspondingly greater thickness of the lighter metals is required to accomplish the same degree of absorption. As a rough working rule it may be stated that the absorption of gamma rays by metals is nearly proportional to the density. Soddy and Russell* have examined the relation between absorption and density and find that the absorption for the following materials increases in the order named:

Paraffin wax, sulphur, glass, aluminum, zinc, tin, iron, brass, copper and lead.

SECONDARY RAYS

Besides the three forms of primary radiations already described, there are secondary radiations which are produced when the primary rays impinge on matter. The secondary radiation produced by alpha rays are called "delta" rays, which are analogous in all respects to very slow beta particles. This form of secondary radiation is of no practical importance from the therapeutic standpoint. When beta rays strike a surface, part of them are scattered and turned back on the side of incidence while others are stopped and their energy is converted into secondary gamma rays just as X-rays are produced when cathode particles impinge on a target. There is no evidence of secondary beta rays from primary beta radiation.

Gamma rays, however, in traversing matter produce both beta and gamma secondary radiation. There is a scattering effect when gamma rays pass through a sheet of metal, the transmitted rays emerging in all directions, but the most intense penetrating rays always emerge in the same direction as that of the incident radiation. From the standpoint of therapeutic application, the secondary beta rays produced by the passage of gamma rays through a metal screen must always be considered and an additional absorbing material, such as a few millimeters of rubber, must be provided.

UNITS OF MEASUREMENT

In order to compare the results of various workers in the field of radioactivity, a committee was appointed in 1910

*Soddy and Russell, Phil. Mag., 19, p. 725, 1910.

by the Congress of Radiology at Brussels to prepare a suitable radium standard. Two years later this committee accepted, as the International Radium Standard, a salt containing pure radium chloride prepared by Madam Curie. This primary standard was sealed in a thin-walled glass tube and preserved in Paris. At the same time a secondary standard, prepared by Hönigschmid, was accepted by the committee and preserved in Vienna. Duplicate preparations have since been supplied to the United States Bureau of Standards, at Washington, D. C.

The milligram of radium element determined by a gamma ray comparison with such a certified tube has been adopted as the unit of radium measurement. All tubes and plaques containing radium salts are now sold on the basis of their radium content as certified by the United States Bureau of Standards.

The unit of radium emanation has been named the "curie" in honor of Professor and Madam Curie, the discoverers of radium. The curie is that quantity of emanation in equilibrium with one gram of radium element. For practical purposes one one-thousandth part of a curie, or one millicurie, is the unit almost universally used. Obviously the millicurie is that quantity of radium emanation which exists in equilibrium with one milligram of radium element.

THERAPEUTIC USES

The therapeutic application of radium is based on the fact that the radiations from radioactive substances, if sufficiently intense, are capable of destroying living cells. This effect has proved beneficial in the treatment of disease since the discovery was made that diseased cells are more susceptible to radiation than normal cells of healthy tissue. In other words, the radium rays exercise a selective action, attacking the diseased cells more readily than the normal ones. It may be more accurate to describe this effect as a differential action insomuch as both healthy and diseased cells are attacked, the difference being in the extent of the reaction. By suitable precautions it is possible to effect com-

plete retrogression of a tumor without injury to the surrounding healthy tissues.

Radium for therapeutic purposes may be supplied in the form of any one of several compounds, which generally contain a considerable admixture of the corresponding salts of barium,—an element closely allied to radium in its chemical properties. The purification of such radium salts may be carried to any desired degree, but ordinarily sixty per cent. is a practical limit. The object of further crystallization is to reduce the volume occupied by the crystals of the salt containing a given amount of radium element. Since it is often an object to keep the total volume of the radium tube as small as possible, it is advisable to use an insoluble compound such as the sulphate of relatively high percentage purity. On the other hand, if the radium is not to be used for direct application but is intended to be redissolved to provide a radium solution as a source of radium emanation, a soluble compound is required, preferably the bromide, or chloride, of a purity not over twenty per cent., on account of the reduced danger of loss in opening the tube and transferring to the emanation apparatus. The relatively large proportion of barium present exercises a protective action which lessens the tendency of the radium to precipitate. These and other considerations enter into the selection of the kind and grade of salt, consequently it is always best for a prospective buyer of radium to outline his own particular requirements and permit the producer to recommend the purity and kind of radium compound best adapted to his needs. The following table includes the principal salts of radium which have found application in the treatment of disease:

TABLE II.

Name of Salt	Formula	Solubility	Per Ct. of Ra. Element contained in pure Ra. Salt
Radium Bromide (Hydrate)	$RaBr_2.2H_2O$	Sol. in water	53.6
Radium Chloride (Hydrate)	$RaCl_2.2H_2O$	Sol. in water	67.9
Radium Bromide (Anhydrous)	$RaBr_2$	Sol. in water	58.6
Radium Chloride (Anhydrous)	$RaCl_2$	Sol. in water	76.1
Radium Carbonate	$RaCO_3$	Insol. in water Sol. in acids	79.0
Radium Sulphate	$RaSO_4$	Insol. in water Insol. in acids	70.2

RADIUM IN TUBULAR APPLICATORS

Up to the present time radium has been generally employed in the form of the salt enclosed in a suitable air-tight container. This compound of radium, preferably the sulphate, is sealed in a thin walled glass tube at least two millimeters in diameter and in length no greater than is necessary to hold the firmly packed material; for instance, a tube containing fifty milligrams of radium sulphate may have an external diameter of two millimeters and a length of seventeen millimeters. The sealed glass tube is placed in a metal container which serves in the capacity of a filter.

Unless the physician specifies some particular form of applicator the usual practice of The Radium Company of Colorado is to supply the highly purified radium salt sealed in a very small glass tube, which is encased in a silver tube applicator of one-half millimeter wall-thickness. The silver tube containing the radium is then placed in a nickel-plated, cylindrical, lead-lined container one inch in diameter. Both silver applicator and lead-lined container are provided with screw caps. For convenience in transportation, a small velvet-lined, leather case is used to enclose the whole. One form of applicator tube with outer container is illustrated in Plate I.

RADIUM IN FLAT APPLICATORS

Another form of applicator, designed for the use of radium salt, is the flat type, which may be of any desired size or shape, but is generally provided in the form of a metal plaque from 1 to 4 centimeters square, over which the radium is evenly distributed after being mixed with a suitable varnish or enamel. Five milligrams of radium element per sq. cm. is a convenient concentration of radium in such an applicator.

This concentration of five milligrams per square centimeter constitutes what is known as a full strength applicator. For instance, ten milligrams of radium element distributed over a surface of two square centimeters (1.4x1.4 cm.) produce a full strength plaque. Ten milligrams of radium element applied uniformly over a surface of four

PLATE I.—Radium in Tubular Applicator.

square centimeters (2x2 cm.) result in the half-strength applicator. On the other hand, the same amount of radium element applied to a surface of only one square centimeter (1x1 cm.) constitutes an applicator of double strength.

In the preparation of flat applicators the radium salt is incorporated in a special varnish or enamel which must have properties of resisting various physical and chemical actions, such as repeated sterilization, or immersion in one per cent. solution of potassium permanganate or sodium bisulphate, etc. Most varnishes are somewhat soluble in ether or alcohol, therefore the use of such liquids must be avoided.

With any flat applicator it is a simple matter to employ various screens of sheet aluminum, lead, silver, or platinum for purposes of filtration. The radium plaques are usually supplied with suitable handles, equipped with extensions of various lengths and capable of adjustment to convenient angles. One form of flat applicator manufactured by the Radium Company of Colorado, Incorporated, is shown in Plate II.

RADIUM IN NEEDLE APPLICATORS

Recent developments in radium therapy have introduced the practice of embedding the radium in the tissues to be irradiated. In order to provide a convenient source of radiation for such application the salts of radium may be obtained sealed in hypodermic needles, as illustrated in Plates III and IV.

RADIUM EMANATION

As previously stated, radium emanation may be used in place of radium itself. This practice possesses certain advantages which Dr. W. S. Newcomet,* of Philadelphia, has concisely stated as follows:

> "The emanation of radium may be employed under exactly the same condition as the various salts; it has, however, a wider application, and while its preparation requires some skill, it possesses many advantages, with but few disadvantages. The life of the emanation is very short, as one-half

*Newcomet, William S., M. D., Radium and Radiotherapy—p. 91.

PLATE II.—Flat Applicator with Accessories.

the element is lost in four days, and all in about one month; therefore, where it is to be employed constantly, fresh preparations must be frequently made, and for this purpose a large supply of radium is necessary. However, if a tube containing the emanation is injured or lost, its value is not great compared with the amount of radium required to supply the same activity. The supply can always be secured in the place most advantageous for its preservation and the emanation used as a therapeutic agent at any point within a day's travel."

In regard to the decay of radium emanation it should be borne in mind that the rate at which a given quantity of emanation disintegrates has been carefully determined, making it a comparatively simple matter to calculate the amount remaining after any length of time. There is, therefore, no difficulty in determining correct dosage, except a simple calculation, which slight disadvantage is counter balanced by the decided advantage of adaptability to almost unlimited forms of applicators. When extremely small sources of intense radiation are required, it is possible to collect and purify radium emanation to such an extent that more than 200 millicuries can be put into a fine glass tube smaller than a sewing needle. The tubes ordinarily used measure 2 cm. in length and less than one-half millimeter in outside diameter. It would, of course, be impossible to seal the corresponding amount of radium in the form of any of its salts in a tube of such small dimensions. To go to the other extreme, the emanation may be evenly distributed in large applicators of unusual and special design. These advantageous features of the use of radium emanation may be summarized as follows:

(1) The radium itself is not taken from the apparatus; therefore the danger of loss is reduced to a minimum.

(2) The source of radiation can be concentrated in a small volume or distributed uniformly over a large surface at will. Radium itself cannot be so conveniently arranged to satisfy particular requirements.

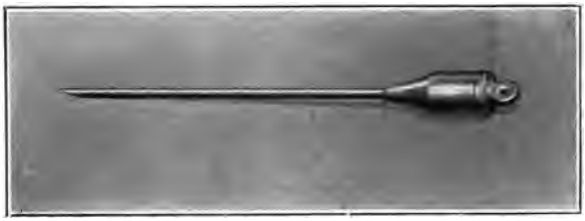


PLATE III.

Needle Applicator.

PLATE IV.

Needle Applicator in Case.

Various schemes have been devised for applying radium emanation in the treatment of disease. Among the most notable methods are the following:

1. The emanation is combined with oxygen and used as an inhalation. This involves a considerable margin of error in administering suitable dosages. Since the effect is primarily upon the lungs, great care must be exercised to prevent injury by over-dosage. The method may be regarded as of minor importance, but several authorities have pointed out that emanation introduced into the lungs by inhalation is undoubtedly absorbed by the blood and therefore may produce far-reaching results.

2. The emanation is dissolved in water and stated amounts used for drinking purposes. This method has received considerable attention, and various forms of apparatus are on the market; but whether such radioactive drinking water possesses any therapeutic value is open to question, because the emanation escapes very rapidly from the water and also from the system after the water has been drunk. In view of the uncertain merits of such treatment, The Radium Company of Colorado, Incorporated, does not endorse this practice.

The best way to use radium emanation is in the form of the purified gas in quantities comparable with the amounts of radium prescribed for direct radiation treatments according to the most highly developed practice of radium therapy. The purified emanation should be sealed in bulbs or tubes and used in exactly the same manner as radium, except in cases where a special form of application is essential. In regard to the use of radium emanation, Dr. Robert Knox, Director of the Electrical and Radio-therapeutic Department of the Cancer Hospital in London, says:*

> "Of the many methods of using radium emanation, the one which commends itself most forcibly is that by which the emanation is placed in receptacles, which can be used in a great variety of ways according to the particular case requiring

*Knox, Robert, M. D., Radiography and Radio-Therapeutics, Part II, p. 499.

treatment. * * * By using a large quantity of radium salt in solution and drawing off the emanation, it is possible to treat a large number of patients by means of specially designed tubes, which can be constructed to suit each particular case. Patients at a distance may receive treatment by means of these applicators, and patients at hospitals may be allowed to go home with the radium emanation applicator, an advantage which is not possible when using the actual radium, on account of its financial value."

The preparation of radium emanation as a radiating source involves the use of some form of apparatus designed to pump the gas out of the radium solution and to remove the hydrogen and oxygen, which are present as impurities. In regard to this phase of the subject, Mr. Failla of the Memorial Hospital, New York, writes as follows:*

"The radium is in the form of radium bromide dissolved in water to which a small amount of hydrochloric acid has been added. The reason for keeping it in solution is to facilitate the escape of the emanation from the radium compound. The glass flask in which the solution is kept is sealed to a glass tube which in turn is sealed to the purifying apparatus, and the whole is kept as free from air as possible.

The radiations from radium and its products act on the water and the hydrochloric acid, and liberate hydrogen, oxygen and chlorine. Hence, when the emanation is first drawn off from the flask, it is mixed with these gases and with a large amount of water vapor. Besides the radiations decompose also organic compounds such as the grease of stopcocks, and so other gases are always present. The volume of the emanation itself is extremely small, but owing to these by-products, the gases pumped out of the flask occupy a relatively large volume. In order to

*Failla, G., EE., A. M., Radium Therapy in Cancer at Memorial Hospital—p. 23.

get a concentrated source of radiation it is necessary, therefore, to get rid of these impurities. There are two methods of accomplishing this result. Roughly speaking we may say that one consists in separating the extraneous gases from the emanation by means of different chemicals; while the other consists in separating the emanation from the residual gases by condensing it by means of liquid air. We employ the first method, which in practice is simpler and very satisfactory for all our purposes. Using the purifying apparatus designed by Professor William Duane we can get the emanation two or three times more concentrated than we ordinarily need it.

After most of the objectionable gases have been removed by the chemicals in the purifying apparatus, by means of mercury pumps the emanation and the residual gas are displaced into a very fine capillary glass tube which has previously been exhausted thoroughly. The portion of the capillary tube containing the emanation is sealed off with a small flame and from it several tubes of the required length are made. In doing this practically none of the emanation is lost, because the pressure of the gases inside the tube is less than the pressure of the air outside, so that, as the glass tube is heated, it collapses and seals itself shut. The tubes as ordinarily used are less than ½ mm. in outside diameter and from 12 to 20 mm. in length."

The apparatus designed by Professor William Duane of Harvard is used for purifying emanation at the Memorial Hospital, New York, and the Huntington Hospital in Cambridge. The Radium Company of Colorado, Incorporated, has placed this type of apparatus on the market and the company is prepared to direct the installation of such equipment in radium emanation stations. The general principles of the Duane apparatus are those previously employed by Ramsey and Soddy, Rutherford, and Debierne. The method

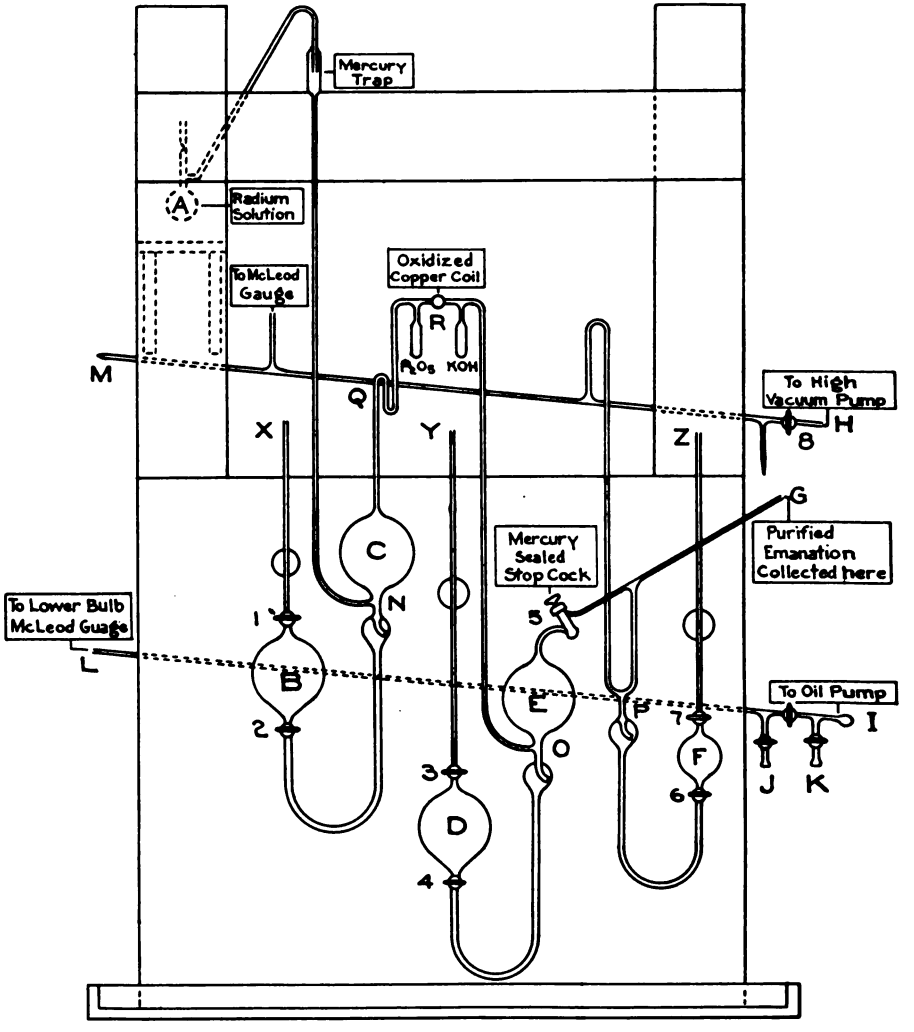
involved has much to recommend it, and to quote Dr. Duane,* the advantages are:

> "that the purification does not require liquid air; that a large number of millicuries of emanation can be purified and compressed into a small fraction of a cubic millimeter, in ten or fifteen minutes of time; that no emanation is lost except that due to its natural decay; and that the process may be repeated a great many times without renewing parts of the apparatus."

Figure I illustrates the elevation of such an emanation apparatus constructed—with the exception of several minor details, according to Dr. Duane's design. A soluble salt of radium, such as the bromide or chloride, is dissolved in pure distilled water to which a little hydrochloric acid has been added, and the solution is sealed in the small glass flask at A. The bulbs B, D, and F, are filled with redistilled mercury through the open tubes x, y, z, which are then sealed. The reservoirs B, D and F are connected above their upper stop-cocks (1, 3, 7 respectively) with the oil-pump line L I, by means of glass tubing (not shown in Fig. I) leading back through the supporting frame of the apparatus. This arrangement permits independent control of the mercury level in any of the reservoirs and connecting lines. By means of a Langmuir mercury condensation pump, backed by an electrically driven two-stage oil-sealed vacuum pump, attached at H, air is removed from the apparatus, and the resulting vacuum is maintained except when replacements may necessitate opening the chemical chambers.

With the mercury standing below connection N, the radium emanation is allowed to accumulate over night or for a longer period if desired, and diffuse into reservoir C. By allowing atmospheric pressure to act on B, mercury is forced into C, thereby carrying the mixed gases up through the trap Q into the chemical chambers at R. At this point

*Duane, William, PhD., Methods of Preparing and Using Radioactive Substances in the Treatment of Disease, and of Estimating Suitable Dosages—Boston Med. and Surg. Journal, Vol. CLXXVII, No. 23, pp. 787-799, Dec. 6, 1917.



RADIUM EMANATION APPARATUS

THE RADIUM COMPANY OF COLORADO, INC.

DENVER, COLORADO.

FIGURE I.—Elevation of Radium Emanation Apparatus.

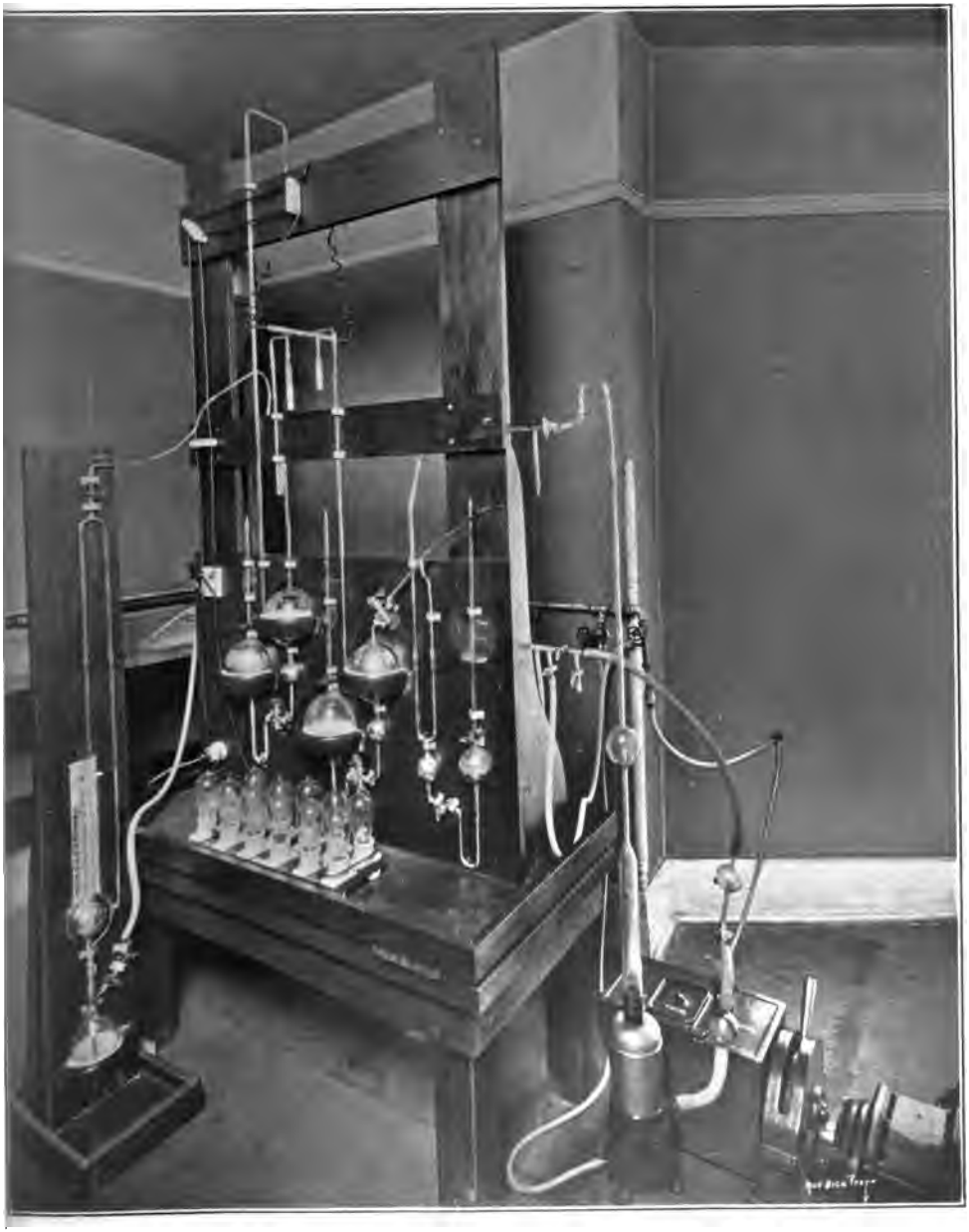


PLATE V.

Radium Emanation Apparatus.

there is a slightly oxidized copper wire coil which is enclosed by a tube lying perpendicular to the plane of the drawing in Fig. I. Upon heating this coil to redness the hydrogen and oxygen present with the emanation as impurities, combine to form water which is absorbed by phosphorpentoxide. The oxidized copper removes any excess of hydrogen, and potassium hydroxide is provided for the purpose of eliminating carbondioxide which may be present in very small quantities. Several minutes are required to complete the reactions. During this period, the outlet from the chemical chambers has been closed by a mercury column in the tube leading from R to E. By evacuating reservoir D, the mercury level in E is brought below connection O, whereupon the purified radium emanation diffuses into E, from which it is forced through stop-cock 5 by again admitting air at atmospheric pressure to reservoir D. After the emanation has passed stop-cock 5, this cock may be closed and thereafter manipulation of the gas and mercury may be controlled by means of stop-cocks 6 and 7. With stop-cock 6 open, atmospheric pressure acting on the mercury in reservoir F forces the purified emanation into any form of tube or container previously sealed on at point G.

The container, which may be either a fine capillary tube, or a larger glass applicator of special design, is removed by fusing the glass connection with a small flame. The gas in the container is still under a slightly reduced pressure, consequently the glass tip seals itself as it is drawn away from the apparatus.

Plate V shows the Duane apparatus with several modifications as installed in the Denver laboratories of The Radium Company of Colorado, Incorporated.

Now that the successful use of radium emanation has been established, it seems that a co-operative plan for the production and distribution of emanation will enable many physicians to enter the field of radium therapy who possibly might have refrained from doing so on account of the large investment required when radium itself is used.

The amount of radium necessary is governed somewhat by the particular requirements of the physicians who intend

to utilize the output of the emanation station. The minimum quantity for ordinary purposes would probably be two hundred milligrams, and almost invariably a greater amount will be a convenience. If a station is provided with five hundred milligrams of radium, the output of purified emanation will be about seventy millicuries per day, allowing ninety per cent. efficiency for the apparatus. In case larger amounts are required, the emanation may be allowed to accumulate two days before collecting, in which case about 135 millicuries may be obtained. After three days' accumulation, 190 millicuries will be available, or after four days about 235 millicuries may be collected. After about thirty days the full equilibrium value will have accumulated, but it is generally advisable to utilize the emanation regularly after only one or two days' accumulation.

A newly collected tube of emanation attains its maximum activity after three or four hours. The gamma radiation is measured by comparison with a standard tube of radium, and subsequent values may be determined by consulting the decay curve in Figure II.

The rate of decay of radium emanation may be, perhaps, more clearly shown by tabulation of the amounts remaining after certain periods of time. By way of example, Table III includes values representing the effective amounts remaining after definite intervals during the first fifteen days after preparation of ten, twenty, thirty, forty and fifty millicuries respectively. For instance, if we start with 50 millicuries of emanation, after one day and fourteen hours 37.6 millicuries still remain effective.

TABLE III.

DECAY OF RADIUM EMANATION

Time		Millicuries				
Days	Hours	10	20	30	40	50
..	2	9.85	19.70	29.55	39.40	49.25
..	4	9.70	19.41	29.11	38.82	48.52
..	6	9.56	19.12	28.68	38.24	47.80
..	8	9.42	18.83	28.25	37.67	47.09
..	10	9.28	18.55	27.83	37.11	46.39
..	12	9.14	18.28	27.42	36.56	45.70
..	14	9.00	18.01	27.01	36.01	45.02
..	16	8.87	17.74	26.61	35.48	44.35
..	18	8.74	17.47	26.21	34.95	43.69
..	20	8.61	17.21	25.82	34.43	43.03
..	22	8.48	16.96	25.44	33.91	42.39
1	0	8.35	16.70	25.06	33.41	41.76
1	2	8.23	16.46	24.68	32.91	41.14
1	4	8.10	16.21	24.32	32.42	40.53
1	6	7.98	15.97	23.95	31.94	39.92
1	8	7.87	15.73	23.60	31.46	39.33
1	10	7.75	15.50	23.25	31.00	38.75
1	12	7.63	15.27	22.90	30.53	38.17
1	14	7.52	15.04	22.56	30.08	37.60
1	16	7.41	14.82	22.22	29.63	37.04
1	18	7.30	14.59	21.89	29.19	36.49
1	20	7.19	14.38	21.57	28.76	35.95
1	22	7.08	14.16	21.25	28.33	35.41
2	..	6.98	13.93	20.93	27.91	34.88
3	..	5.83	11.65	17.48	23.31	29.14
4	..	4.87	9.73	14.60	19.47	24.34
5	..	4.06	8.13	12.20	16.26	20.33
6	..	3.40	6.79	10.19	13.58	16.98
7	..	2.84	5.67	8.51	11.35	14.18
8	..	2.37	4.74	7.11	9.48	11.85
9	..	1.98	3.96	5.94	7.92	9.89
10	..	1.65	3.31	4.96	6.61	8.26
11	..	1.38	2.76	4.14	5.52	6.90
12	..	1.15	2.31	3.46	4.61	5.77
13	..	0.96	1.93	2.89	3.85	4.82
14	..	0.80	1.61	2.47	3.22	4.02
15	..	0.67	1.34	2.02	2.69	3.36

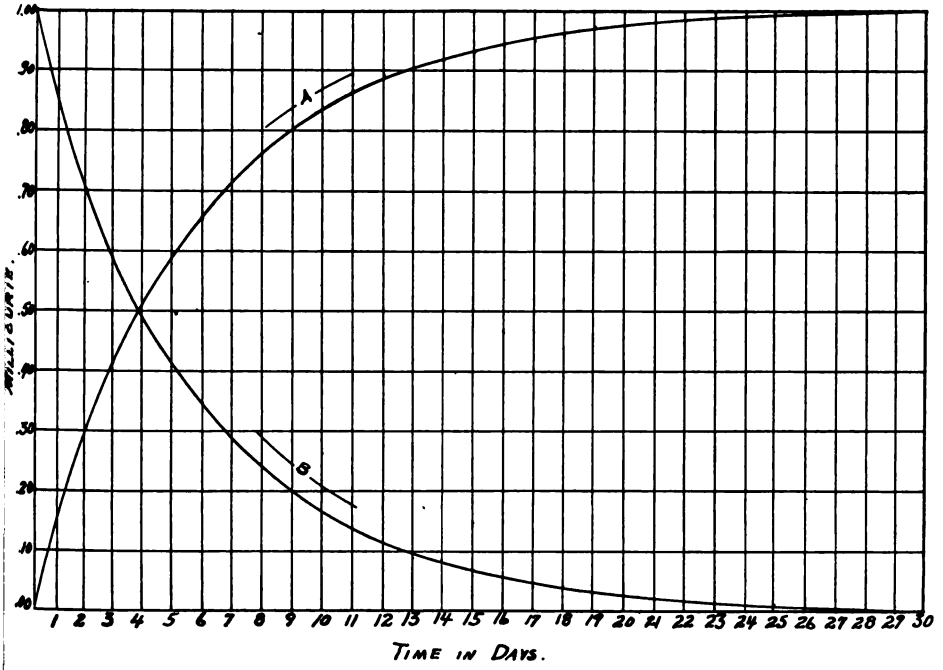


FIGURE II.

(A)—Accumulation, (B)—Decay of Radium Emanation.

ACTIVE DEPOSIT

Attention has already been directed to the fact that the active deposit of radium emanation may be used for therapeutic purposes. This is accomplished by allowing the purified emanation to remain in contact with a few grains of fused sodium chloride until the maximum amount of RaA, B and C are deposited. The emanation is then withdrawn and the salt bearing the active deposit is dissolved in pure distilled water, which results in a very intensely radioactive solution. By using the proper weight of salt and a calculated volume of water, a physiological salt solution may be obtained. Since the active deposit is subject to a rapid rate of decay, such solutions must be used without delay. The customary method of application of the active deposit is by intravenous injection.

DOSAGE[1]

In order to duplicate treatment exact conditions must be specified. The chief factors involved are: the intensity and distribution of radiation, the time of exposure, the filtration and the distance of the applicator from the lesion as well as from healthy tissues. If radium is used as the radioactive source, the best practice is to specify the quantity of radium element in milligrams. In the case of the emanation the unit is the millicurie, which is the equilibrium amount of emanation corresponding to one milligram of radium element. Sometimes the intensity of the radioactive source and the time of exposure are expressed in one as a product—milligram hours or millicurie hours. In general this is a regrettable practice, because it leads people to think that the only factors which enter into the specification of a dose of radiation are quantity and time, whereas filtration and distance are just as important. Moreover, if nothing is said about the quantity of radioactive material used or the length of exposure, it is impossible to tell whether a very small amount was used for a long time or a very large amount for a short time. It is certain that in these extreme cases the therapeutic effect in general would not be the same. There is evidence tending to show that for lesions involving the mucous membrane a long prolonged application is better than a short intensive treatment, while for skin conditions the opposite seems to be true. The physiological effect depends largely on the total ionization per unit volume of the part irradiated. It follows then that, within the proper limits, the same result may be obtained by increasing the quantity in the same proportion in which the time of exposure is decreased and vice versa. Extreme variations, however, are not covered by this rule. For instance, we cannot expect to produce the same result by applying 1 milligram of radium for 100 hours as that produced by 100 milligrams for 1 hour.

[1]This section contributed by a specialist in radium therapeutics.

There are many other factors which affect the result, such as the nature and location of the diseased tissues, the idiosyncrasies of the patient, etc., so that the matter of dosage has to be determined largely by experience.

The question of filtration needs careful consideration. It is the filter which determines whether the radiation used for the treatment consists largely of beta rays or gamma rays. There is no evidence at the present time that the nature of the reaction in the two cases is different. In fact, physical considerations lead us to believe that the gamma rays act indirectly by producing secondary beta rays first. But the extent of the reaction is enormously different. It is evident that beta rays can be used to advantage in some cases and gamma rays in others. When radium is lightly screened the effect is mostly due to beta rays; if it is heavily filtered (by 2 or 3 mm. of lead, for instance) it is due to the gamma rays. Hence it is important that the radioactive source at our disposal possesses a high degree of flexibility as regards filtration.

By interposing different thicknesses of lead (or any other material) between a radium tube and a beta ray electroscope, it is readily shown that the beta and soft gamma rays are very easily absorbed. A plate of lead 2 mm. thick will reduce the intensity of radiation to about 3% of that of the unscreened radium. The quality of the radiation is also changed considerably by filtration. After absorbing the beta and soft gamma rays, the decrease in radiation intensity by further screening is small, since the gamma radiation which is capable of passing through 2 mm. of lead is very penetrating. For most therapeutic treatments, therefore, a screen of 2 or 3 mm. of lead or its equivalent is all that is necessary.

Screens of known thickness are required with metallic tubes of radium salts. These may be provided in the form of larger tubes of silver or platinum, or a sheet of lead which may be rolled around the tubes of radium. In all cases it must be remembered that a secondary radiation is set up in a filter and a further screening is necessary to prevent injury to the tissues from this source. Rubber tubing of ½ to 4 mm. thickness will effectively absorb such secondary

radiation. In distant applications, the air between the source of radioactivity and the body will absorb the very soft secondary beta rays which otherwise would be injurious to the skin.

But this is simply incidental. The real reason for applying the radium at a distance is to obtain more uniform radiation for deep treatment without injuring the skin. This comes about as follows: The source gives off rays in all directions. As these rays in general diverge, the intensity of radiation is greater near the source than far away. In the special case of a very small source, the intensity decreases as the square of the distance. For example, if the intensity is assumed to be 1000 units at a distance of 1 cm., it will be $\frac{1000}{4}$=250 at 2 cm., $\frac{1000}{9}$=111 at 3 cm., $\frac{1000}{16}$=62.5 at 4 cm., etc. It will be seen that, as we move away from the source, the intensity decreases very rapidly at first, but more slowly as the distance increases, for the above mentioned example. The difference between the intensity at 1 cm. distance and that at 2 cm. is 750, while the difference between the intensity at 3 cm. distance and that at 4 cm. is only 48.5. The radiation is more uniform the further from the source, but the intensity is less. In practice, advantage is taken of the increase in uniformity of radiation with distance in the treatment of deep seated conditions. The problem is still further simplified by the fact that cancer tissue is more susceptible to the radiations than normal tissue. By proper choice of filter and distance, it is possible to affect a deep seated tumor without injury to the healthy tissue intervening between the radiation and the tumor. "Cross-firing" may be used to advantage in some cases. In any case the filter, the distance and the amount of cross-firing should be adjusted so that the desired result is accomplished with the minimum number of milligram-hours.

PRODUCTION OF RADIUM

The salts of radium produced by The Radium Company of Colorado, Incorporated, are obtained principally from ore mined in the Paradox Valley of Colorado and adjoining districts of Utah. Among the factors contributing to the relatively enormous cost of production of radium, are the following: the careful hand sorting of ore; the fifteen-mile packing of ore on the backs of burros; the transfer of ore to wagons and subsequent seventy-five mile haul to the nearest railroad; transfer of the ore from wagons to the narrow-gauge railroad cars and the two-hundred mile transportation to the junction of the narrow-gauge railroad with the broad-gauge line; reloading into broad-gauge cars and final 125 mile freightage to the mill in Denver. Here the ore is crushed, ground and screened, preliminary to a chemical treatment whereby the radium contained in the ore is extracted and purified.

Some intimation of the extreme care required in the successful chemical treatment of radium-bearing ore may be obtained by consideration of the fact that four thousand pounds of ore must be treated to obtain barely ten milligrams of radium element. As in all methods of extracting radium, the element is recovered with a considerable admixture of barium, and the first product must be further purified by fractional crystallization. The ultimate product is a radium salt of a high degree of purity.

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